Status of Degradation Rates and Mechanisms in Nickel-Hydrogen Cells

15 April 1998

Prepared by

L. H. THALLER
Electronics Technology Center
Technology Operations

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THE AEROSPACE CORPORATION
El Segundo, California

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The usable energy density of nickel-hydrogen cells intended for low Earth orbit (LEO) applications can be significantly increased by cycling them to deeper depths of discharge (DODs). In reviewing the existing life cycle databases, the cycle life has been found to vary from less than 1000 cycles to more than 50,000 cycles when cells were cycled to 60% DOD. The causes for this wide disparity occur during the four major phases in a cell's life: (1) design, (2) manufacturing, (3) storage, and (4) life cycle testing. This report will focus on how the conditions selected for life cycle testing can have a significant impact on the usable life of a cell. Cycle life can be significantly reduced when recharge conditions are selected that accelerate the degradation rates of the naturally occurring degradation mechanisms. By paying close attention during the design, manufacturing, and storage phases, cycle lives can be dramatically improved when accompanied by appropriate recharge conditions. The objective of this study is to examine the cycling potential of nickel-hydrogen cells when cycled to 60% DOD.

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1. Background

Life cycle testing of nickel-hydrogen individual pressure vessel (IPV) cells has been conducted over the last 20 years with some encouraging and some discouraging results (Refs. 1, 2). The latest reports of Air Force- and NASA-sponsored testing characterize a wide spread in the cycle life of the cells to failure, particularly at 60% depth of discharge (DOD). Probably the most encouraging testing, which is still ongoing at 60% DOD, is being carried out on cells designed by the NASA Lewis Research Center (LeRC) and built by Eagle Picher Industries.[*] The technologist might ask why some cells perform poorly and others perform in an outstanding manner. The spacecraft designer, on the other hand, only sees a wide dispersion in terms of cycle life performance. Therefore, the designer is not sure of the best way to use these cells in the power system. An admirable goal would be to understand the potential cycle life expectations for these cells if their designs were optimized to accommodate changes as the cells were cycled.

Certain trends are becoming clear when attempting to categorize the different stress levels of cells that are thought to be similar in design. Life cycling studies have shown (Refs. 3, 4)[**] that 26% potassium hydroxide (KOH) cells last longer than comparable 31% KOH cells, that back-to-back cells usually outperform recirculating cells, and that cells cycled to 60% DOD at 10°C tend to last longer than cells tested at -5°C. Cell fill data indicate that cells with electrolyte quantities less than 2.8 g/Ah tend to be prone to premature failure due to dry-out, while cells with more than 4.8 g/Ah tend to be overly wet and can exhibit popping damage, leading to internal short circuits. Likewise, cells with catalyzed wall wicks outperform comparable cells without catalyzed wall wicks. On the other hand, these trends and results may just be a reflection of the quality of the positive plate, the electrolyte fill amount, the thermal environment of the test, the charging protocol, or the recharge ratio. With this wide variety of possibilities and the span in the most recent life cycle testing results (Figure 1), it is difficult to quantify the usable energy density of nickel-hydrogen cells and batteries with any degree of certainty. Newer configurations and cell chemistries with higher projected energy densities than nickel-hydrogen are being developed in an attempt to displace this technology as the system of choice for aerospace applications. It is not known whether these higher projected energy densities are being made relative to "good" cells, "bad" cells, or "average" IPV nickel-hydrogen cells.

This report will review selected results available from life cycle data basing programs conducted under simulated low earth orbit (LEO) cycling regimes. By reviewing these results, along with the recent results of posttest analyses, we can better understand the factors involved in accelerating the naturally occurring degradation mechanisms.

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[*]Unpublished NASA LeRC data.
[**]T. B. Miller, NASA LeRC (private communication).

2. Causes of Premature Failures

Based on posttest analyses of failed cells, the reasons for abbreviated cycle lives during long-term life cycle testing programs can be attributed to one or more of four major categories of causes.

1. **Cell designs that are unable to accommodate the structural and physical changes that occur during cycling.**

   Cells must be designed to be able to accommodate the changes that take place over the course of the expected cycle life (Refs. 5,6). These changes include plate expansion, plaque corrosion, and gamma phase formation. Provisions for adequate gas and electrolyte management processes must also be made, and water transport to colder portions of the cell wall must be minimized.

2. **Manufacturing difficulties that are usually associated with the structure of the nickel electrode.**

   The main manufacturing factors affecting cell performance are the pore size and pore size distribution of the plaque material, the distribution of active material within the plaque, the electrolyte fill amounts, and the activation procedure. These factors must be watched very carefully; information on them is typically not available in the open literature.

3. **Capacity fading due to the chemical interaction of hydrogen gas with the cobalt additive in the nickel active material (Ref. 7).**

   This capacity fading usually occurs before cycling begins. Most modern cell designs utilize positive precharge. "Hydrogen sickness," as it is called, is much less of a problem than it was when cells were constructed with hydrogen precharge. The amount of nickel precharge used depends on the expected wet storage requirement of the completed battery.

4. **Conditions selected for the recharge step of the cycle that have been shown to accelerate the rate of performance and capacity fading.**

   Once the cells or batteries have moved into the cycling phase, excessive amounts of overcharge (ratio of ampere hours of charge to ampere hours of discharge) can result in the following problems.

a. Excessive amounts and rates of oxygen formation inside the porous structure of the nickel electrode. This oxygen formation can break up the sintered connections between the carbonyl nickel particles forming the skeleton of the electrode. The result is an increase in the distance the electrons must travel to reach the active material. Expansion of the nickel electrodes is also possible under these conditions.

b. High end-of-charge voltages, resulting in excessive oxidation of the nickel substrate material. This corrosion weakens the sinter and gradually increases the voltage drop between the current collector and the active material. Weakened sinter structures are also prone to expansion.

c. A larger amount of the active material being charged to the gamma phase. This phase is less dense than the beta phase material and results in expansion of the plate thickness.

d. A process that prevents some of the active material from being properly charged. This phenomenon is not fully understood at this time but appears to be reduced as the concentration of the KOH used as the electrolyte is lowered.

All of the issues listed in the preceding four categories are important in designing power systems for deep DODs in LEO applications.

3. Span of Cycle Life

The histogram of Figure 1 displays the results from several different LEO life cycle data basing programs. These programs have been carried out under different sponsors, at different testing facilities. The testing has been done either at the Martin Marietta (now Lockheed Martin Astronautics [LMA]) facility in Denver, Colorado, at the Navy facility in Crane, Indiana, or at NASA LeRC in Cleveland, Ohio. The sponsors include several organizations within the Air Force, NASA LeRC, and NASA's Space Station activity. All the tests at 60% DOD were examined for these programs. It must be remembered that "IPV nickel-hydrogen" is a rather generic term that includes many hundreds of possible permutations and combinations of electrode types and thicknesses, separator materials, manufacturing methods and processes, and assembly and activation procedures. In these testing programs, cells were cycled at different temperatures using several different recharge protocols. If one were to suggest a cycle life for IPV nickel-hydrogen cells at 60% DOD, very specific information related to the cell design and cycling conditions would be required as a minimum. A large percentage of cells that cycled 10,000 or fewer times were those with "advanced designs." The best performing design was one that featured catalyzed wall wicks, 26% KOH as the electrolyte, and moderate recharging conditions. Catalyzed wall wicks were introduced (1) to reduce the thermal gradients with the cell and (2) to reduce the damage of the hydrogen electrode caused by the recombination of hydrogen with the oxygen generated during the latter portions of the recharge step (Ref. 8). This unique feature helps the internal elements of the cell to run cooler by facilitating the recombination of oxygen and hydrogen on the wall of the cell. Damage to hydrogen electrodes has resulted in the development of internal short circuits leading to cell failure. The major question following a review of the 60% DOD information was why some cells did so well and why others did so poorly.

Since the initiation of these testing programs, new information has become available, thanks to the researchers in this field. This information suggests that there are better ways to formulate a cell design and more data to help explain the functioning of the nickel electrode. These data, along with the results of these cycling programs, have helped explain the impact of certain recharge conditions on the cell's cycle life.
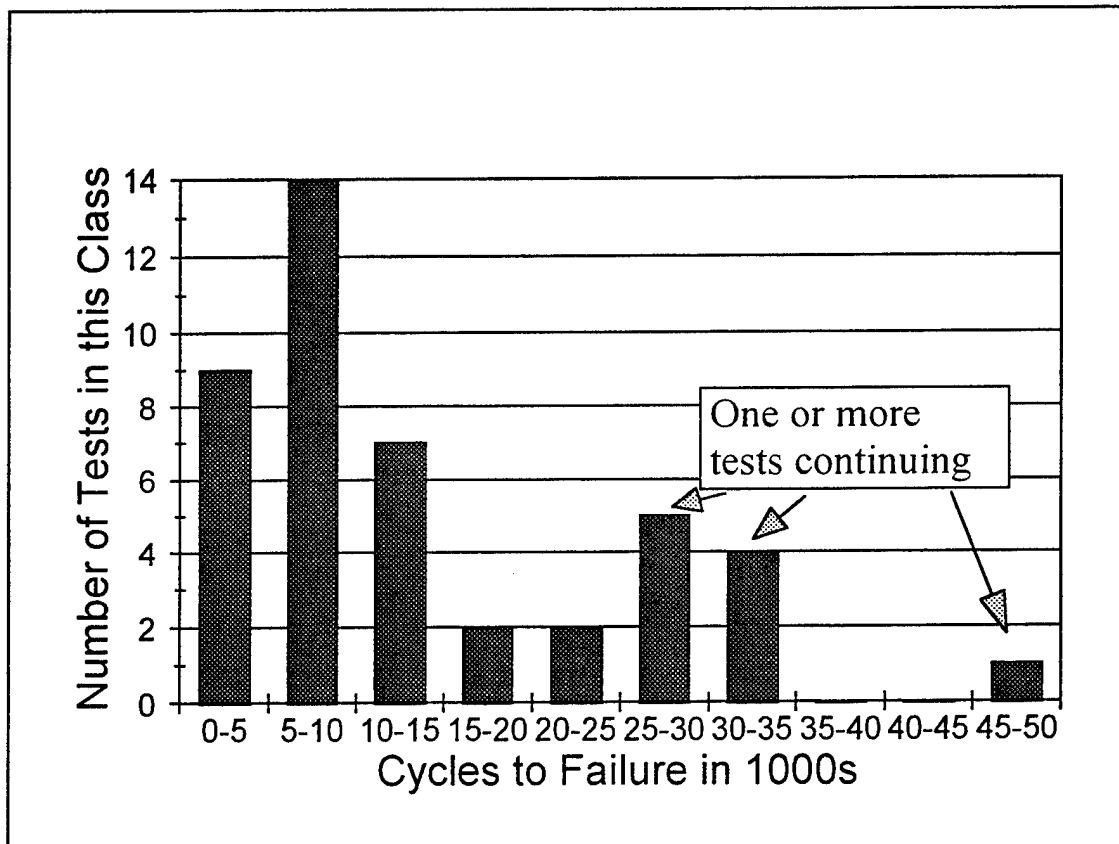
Figure 1. Database of tests at 60% DOD. (Sources: Air Force, Martin Marietta [MM], NASA LeRC, NASA Space Station Alpha [SSA].)

4. Degradation Mechanisms

Degradation mechanisms that are associated with nickel-hydrogen cells have been studied for many years by a number of investigators. If only well-designed and assembled cells are considered here, a small number of unavoidable processes are still present that take place over the course of cycling. These processes include (1) corrosion of the nickel substrate, (2) expansion of nickel electrodes, and (3) reduction in the electrochemical utilization of the doped nickel hydroxide. (One aspect of this third process is discussed in Section 4.3: Deactivation of Active Material.) Each of these processes results in the loss of usable cell capacity. The rate at which each of these processes proceeds depends very much on the concentration selected for the electrolyte and the conditions set for the recharge mode. Each of these factors will be addressed in the following sections of this report. Recommendations will be made, based on the experience of the different life cycle data basing programs, the results of posttest analytical studies, and the current understanding of the functioning of the active material within the nickel electrode.

4.1 Corrosion of the Nickel Substrate

It is well established that as nickel-hydrogen cells are cycled, the nickel plaque will corrode due to electrochemical oxidation during the recharge step. The reaction at the nickel electrode proceeds as follows:

$$Ni + 2OH^- = Ni(OH)_2 + 2e^- \qquad (1)$$

The reaction at the hydrogen electrode is given below:

$$2H_2O + 2e^- + 2OH^- + H_2 \qquad (2)$$

By adding the two portions of this electrochemical oxidation, it is seen that as the nickel is corroded, water from the electrolyte (increasing its concentration) is consumed and hydrogen gas is evolved. The amount of hydrogen formed in parallel with the nickel corrosion products is a convenient measure for estimating the amount of nickel corrosion. Estimates made using the increase in end-of-charge pressure over the course of the cycle life of the cell have been confirmed from destructive physical analysis (DPA) carried out on these same cells in our laboratories. The rate of plaque corrosion is related in part to the cell voltage during recharge (end-of-charge voltage) and in part to the ease with which the surfaces of the nickel sinter can be oxidized. In reviewing the data from the long-term cycling studies supported by the above-mentioned Air Force and NASA cycling programs, we found the pressure rise per 1000 cycles to be variable (Figure 2). The histogram in Figure 2 shows the wide variability for cells cycled to 60% DOD. A further study was conducted on the impact of the conditions selected for the recharge portion of the cycle. The study used all of the available database information (Figure 3). All of the tests carried out at different DODs were examined, and the corrosion rates were estimated from the
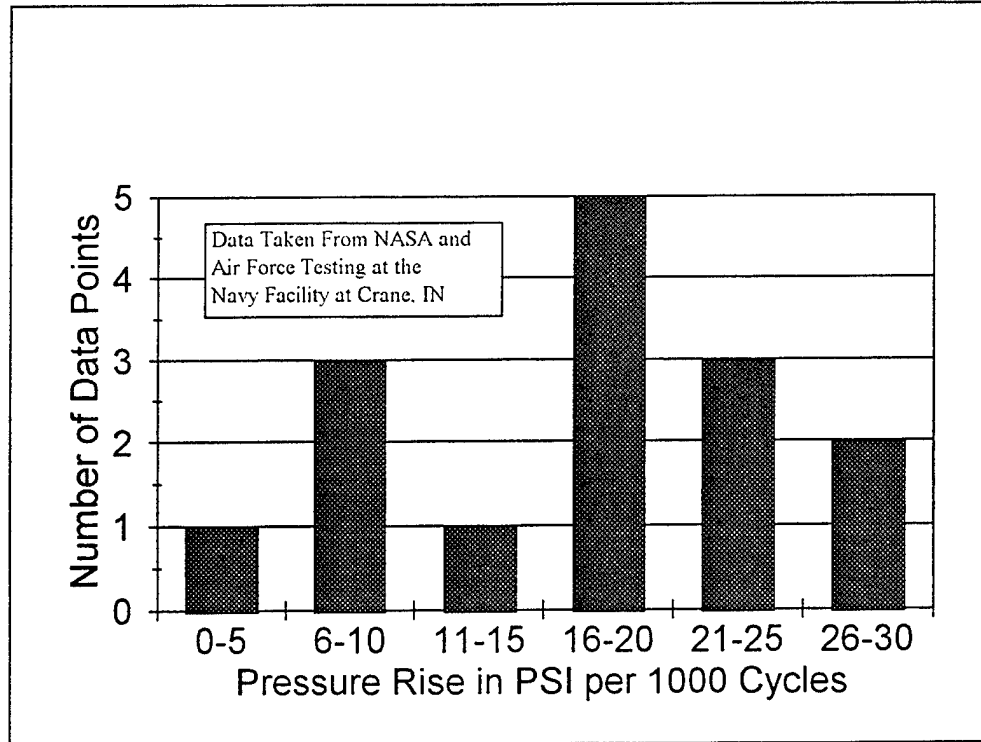
Figure 2. 60% DOD plaque corrosion, estimated from pressure trends.
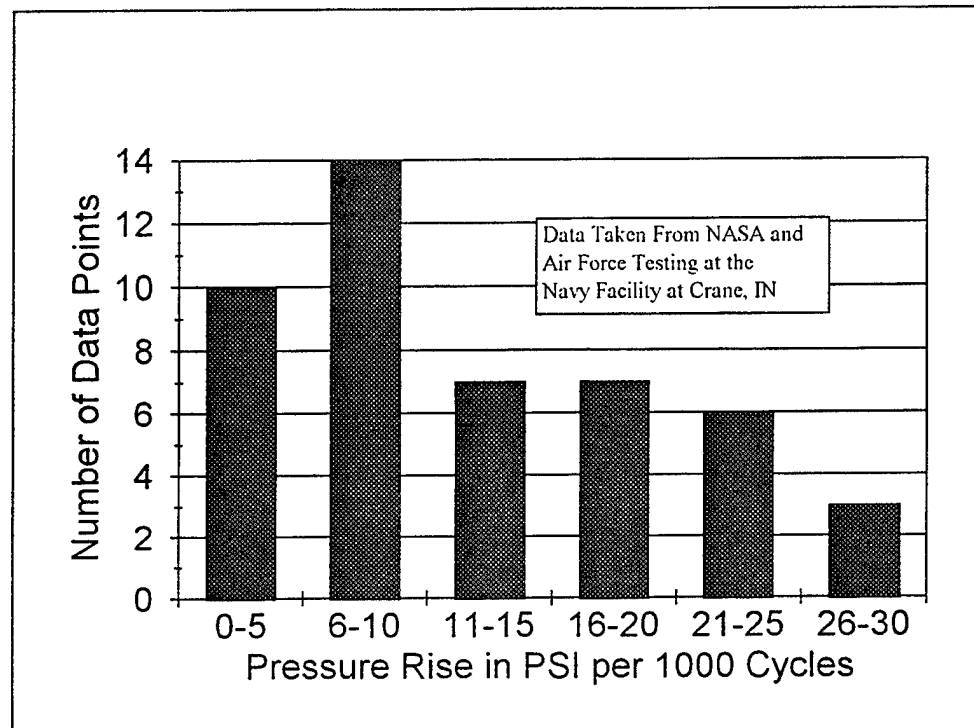

Figure 3. Plaque corrosion—all DODs, estimated from pressure rise.

slope of the end-of-charge pressure (Figure 3). The database used for the study included cells manufactured by SAFT Battery Company, Eagle Picher, Hughes Aircraft Corporation, Gates Aerospace Batteries, and Yardney Technical Products. The testing programs were supported by one of several different Air Force or NASA organizations and were carried out at the Navy facility at Crane, Indiana. The variables studied included DOD, end-of-charge voltage, recharge ratio (RR), KOH concentration, and test temperature. No strong evidence was found for differentiating between cell manufacturers or plaque types, except for the passivated plate material used in a special test sponsored by NASA LeRC.

As the substrate material is corroded away, the plaque becomes weaker and therefore less able to resist the expansion tendencies caused by the active material contained within its porous structure. As the juncture of the individual nickel particles is corroded, the electrical resistance of the conductive network is reduced, leading to a higher internal cell resistance. A further complication of corrosion is associated with the nickel hydroxide formed in this manner. This nickel hydroxide is similar to the normal active material, except that it does not contain the cobalt additive. Without the cobalt additive, the nickel hydroxide has a different half-cell potential, which reduces the over-potential for the evolution of oxygen. The lack of cobalt additive also results in potential differences within the active material. The electrochemical utilization of this undoped form of nickel hydroxide is not as high as that of the doped form. The presence of undoped material also reduces the electrochemical utilization of the normal cobalt-containing nickel hydroxide. This reduction is determined by comparing the chemical analysis of plate material samples with the results of the electrochemical utilization tests.

4.2 Expansion of Nickel Electrodes

Expansion of nickel electrodes during cycling is a well known degradation mechanism. It is generally attributed to: (1) the generation of oxygen in the internal pores of the electrode during overcharge, and (2) the difference in lattice constants between the crystalline forms that are generated over the course of the charge and discharge processes. In particular, when cells are repeatedly cycled to the gamma phase, large amounts of plate swelling are noted during subsequent posttest analyses. Reference 9 lists the "c" spacings of the lattice of the different forms as follows: alpha $Ni(OH)_2$, 8–9 Å; beta $Ni(OH)_2$, 4.6 Å; beta NiOOH, 4.7 Å; and gamma NiOOH, 7.2 Å. Large amounts of the gamma phase result from extended periods of overcharge, depressed temperatures, and the use of higher concentrations of KOH as the electrolyte.

4.3 Deactivation of Active Material

Deactivation of active material is not well understood but is seen from time to time in the examination of cells that have suffered large amounts of capacity loss. Its signature is an increase in the difficulty to charge the oxyhydroxide to the gamma phase. The next section of this report will cover some laboratory results that address this phenomenon.

5. Results of Posttest Analyses

Posttest analyses carried out in our laboratories were reviewed to assess the impact of the three degradation mechanisms (discussed in Section 4) on the performance and life of IPV nickel-hydrogen cells. Other analyses reported in the open literature or made available to this study were also reviewed. Cells were selected that were representative of those severely stressed, or only lightly stressed, during their life cycle tests. The following measurements were made:

1. **Plaque corrosion.** Estimated from pressure rise during cycling, from loss of weight of the nickel substrate, or from gain in weight of the active material.

2. **Plate expansion.** Physical measurements.

3. **Utilization of active material.** Capacity of 1 cm^2 electrode divided between that which is usable, residual, and unavailable, by discharging the electrode after charging it in the first cycle for 16 hr at 2 mA/cm^2, and then charging it in a second cycle for 32 hr at 2 mA/cm^2.

In a new cell, the active material is composed of a partially hydrated nickel hydroxide that is doped with cobalt. The cobalt ions are located in some of the lattice sites normally occupied by nickel ions. The cobalt dopant is responsible for three important changes to the undoped nickel hydroxide. First, the dopant lowers the tendency of the nickel electrode to form oxygen as it approaches full charge. Second, the dopant changes the compressibility characteristics of the active material, making it more compliant. Third, and most important, it reduces the resistance to the flow of electrons, or protons, or both, in the discharged form of the active material. This reduction in resistance increases the amount of capacity that can be removed from a cell before the cell voltage drops below a usable value.

5.1 Plaque Corrosion Results

As the substrate undergoes corrosion, nickel hydroxide is formed at the surface of the nickel sinter substrate. The material becomes potentially available to act as additional active material. However, it does not contain cobalt in its lattice structure. This results in a gradual increase in the internal resistance of the cell as a whole and a reduction in the ampere hour capacity as measured to a selected voltage cutoff, such as 1.0 V. Analyses of samples of plate material after testing typically show an increase in the "amount" of active material based on the analyses for nickel hydroxide, but a reduction in the usable capacity, because of the reduced ability to electrochemically utilize the mixture of materials that are now contained in the electrode. The results of one of the cells analyzed in our laboratories showed that the gain in active material through corrosion of the nickel plaque was more than offset by a decrease in the electrochemical utilization of active material. In the

electrodes studied at Aerospace, there was close agreement between with the capacity measurements performed at Crane, when the cell was removed from testing prior to failure, and the results of our electrochemical utilization tests on samples of electrode material taken from this cell.

The degree or rate of corrosion is related in part to the cell voltage during recharge (end-of-charge voltage) and in part to the ease with which the surfaces of the nickel sinter can be oxidized. The cell that was cycled under the less stressful conditions (referred to as cell 2) had a pressure rise of about 10 psi per 1000 cycles. This pressure rise translates to a rate of corrosion that would result in about 25% loss of the nickel substrate after about 8 years of LEO cycling under the modest recharge ratios of 1.03 to 1.04. These corrosion estimates from the pressure trends have been confirmed in posttest analyses carried out in our laboratories. Results from the NASA-funded Hughes study (cell 1) have shown that corrosion percentages as high as 40% can be tolerated without undue loss of cell performance. This amount of corrosion can most likely be reduced using techniques that were common with nickel-cadmium cells, where erratic nickel plate corrosion was a problem during the manufacturing of the nickel electrodes. A "passivation" process was used to introduce an oxidized surface onto the surface of the raw plaque. NASA LeRC has reported[*] cycling nickel-hydrogen cells that were made with a passivated plaque material. In this test, three cells were made, using plaque material that had been passivated. These cells were cycled, along with three cells that were made using plaque material that had not been passivated. The cells using passivated plaque showed about one-half the pressure rise over the first 20,000 cycles compared to the cells not using passivated plaque.

Using 58 data sets (shown in Figure 3), a multidimensional regression analysis was carried out to estimate the effects of the five above-mentioned variables (temperature, recharge ratio, end-of-charge voltage, concentration of KOH, and DOD). Only about 80% of the variance was captured using the data sets that were available. It was interesting to note that, as expected, when the variables were all lowered, there was a noticeable reduction in the rate of corrosion of the nickel substrate. A pressure rise of only about 5 psi/1000 cycles is desirable to ensure a long cycle life without any problems with excessive plaque corrosion. This pressure rise also ensures an end-of-life pressure that will not be dangerously close to the leak-before-burst pressure limit for the cell case. The cells displaying the largest amounts of plaque corrosion were those that had been subjected to the most aggressive recharging conditions. Figure 4 shows a comparison of the corrosion rates for cells cycled at 35% DOD with the rates of cells cycled at 60% DOD. In general, the corrosion rates are higher at the deeper DODs, but there are data points having acceptable corrosion rates at the deeper DODs. The impact of the variables can be ranked, as follows:

1. Test temperature was the most significant variable, accounting for about 30% of the corrosion.

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[*]Unpublished NASA LeRC data.

2. Recharge ratio, DOD, and end-of-charge voltage each contributed about 20% to the corrosion.

3. KOH concentration only accounted for about 10% of the corrosion.

5.2 Plate Expansion Results

In one comparison, plate material from two cells cycled under very different conditions was selected as an example of a severely stressed and a moderately stressed cell. The severely stressed cell had been tested by Hughes under a NASA contract, with the results reported in detail elsewhere (Ref. 10). The moderately stressed cell was also a Hughes cell, which had been cycled as part of the Air Force data basing program and was made available to Aerospace for analysis. This second cell was made with plates manufactured by the dry powder process and cycled 42,000 cycles at 40% DOD. It showed only about 6% average expansion of the nickel electrodes. In the earlier Hughes study done under the NASA contract, similar plate material was used, and boiler plate cells that were cycled for about the same number of cycles expanded up to 80%. Some of the plate expansion was taken up by compression of the plastic gas screens. In fact, some of the expansion of the plate was due to active material coming out of the porous nickel structure and forming a "mush" on the surface of the more rigid nickel sinter structure. As noted above, the cells used in this study were aggressively overcharged (recharge ratio of 1.1) and had end-of-charge voltages as high as 1.64 V. The rate of expansion is therefore a variable that is strongly dependent on the recharge conditions.

5.3 Decrease in Utilization of Active Material Results

The major cause of reduced utilization of active material is corrosion of the nickel substrate and its effect on the conductivity and over-potential for oxygen evolution. This topic was covered in detail in Section 5.1. A second cause of reduced utilization is active material (that is intended to be contained inside the fine pore structure of the electrode) extruding out onto the surface of the electrode or into the porous structure of the separator material. Outside of the pore structure, this active material can become electrically disconnected from the current collector. The material can also lose contact with the conductive matrix while it is still within the pore structure of a substrate with a large pore size. A third cause of reduced utilization is the expansion of the electrode structure accompanied by the fracturing of some of the junctures of the individual sinter particles. The signature for this situation is a very large amount of capacity that can only be discharged at very low discharge rates (C/100). A fourth cause was noted by examination of the data appearing in the Hughes study (Ref. 11) and in a report from a Comsat study (Ref. 12). Apparently, reduced utilization of the active material can result from a process that is associated with the potassium hydroxide concentration used as the electrolyte within these cells. This phenomenon is not too clearly understood at this time.
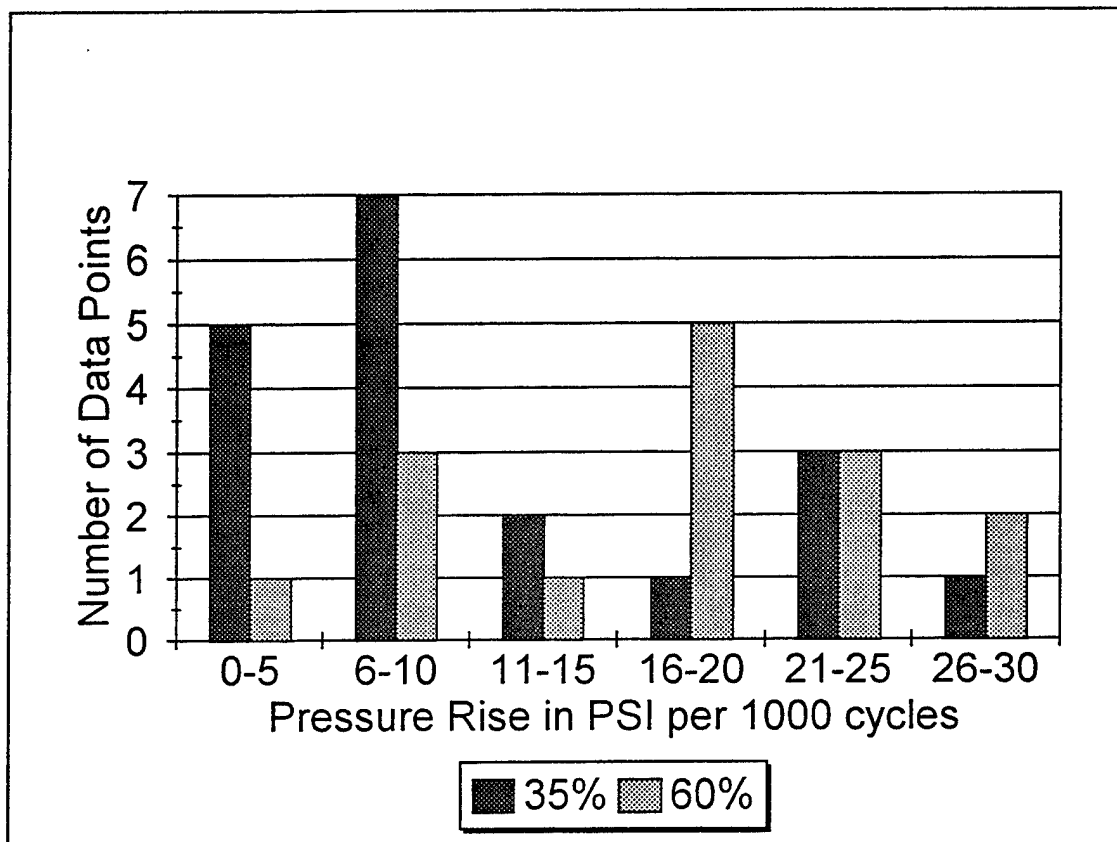
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Figure 4.   Corrosion rates at 35% and 60% DOD, estimated from pressure rise.

Results from these two studies have found that when lower concentrations of the potassium hydroxide are used as the electrolyte, the rate of this fourth type of reduction in utilization is reduced. Under some conditions of stressful cycling, electrodes were found to lose capacity without the plates expanding or corrosion taking place. This fourth cause is currently under investigation in our laboratory and is referred to as "deactivation of active material." It is felt that a complete understanding of this fourth cause is critical for the accurate projection of long cycle life at deep DODs.

Table 1 illustrates the reduced utilization caused by plate expansion and plaque corrosion in the IPV nickel-hydrogen cell. There is no evidence for reduced utilization caused by deactivation of active material in this particular cell. The existence of this phenomenon is precluded by the fact that a significant amount of the remaining active material can be charged to the gamma phase.

Table 1. Impact of Corrosion and Expansion on Utilization

	Cell A	Cell B	Cell C
DOD	60%	60%	60%
Cycles to failure	6500	10000	10500
Nickel corrosion	17%	17%	15%
Plate expansion	31%	23%	35%
Utilization after 32 hr	88%	90%	85%
Utilization when new	120%	120%	120%
Gamma phase after 32 hr	20%	25%	23%
Capacity ratio 32 hr/16 hr	1.22	1.28	1.32

The results shown in Table 1 indicate premature failure of the cells due to an aggressive recharge protocol. Figure 5 shows an approximate voltage vs time plot of cycle 500 and cycle 6500 for cell A. The recharge sequence called for a return of 100% of the discharged capacity during the first portion of the recharge, followed by a reduced rate of charge such that the total recharge ratio would be 104%. Note the high voltage attained just before the cutback of the charge rate to the reduced rate of charge portion of the recharge. A less aggressive recharge protocol might add a cutoff voltage near the end of the high rate portion of the recharge, followed by a higher current during the latter portion of the recharge.
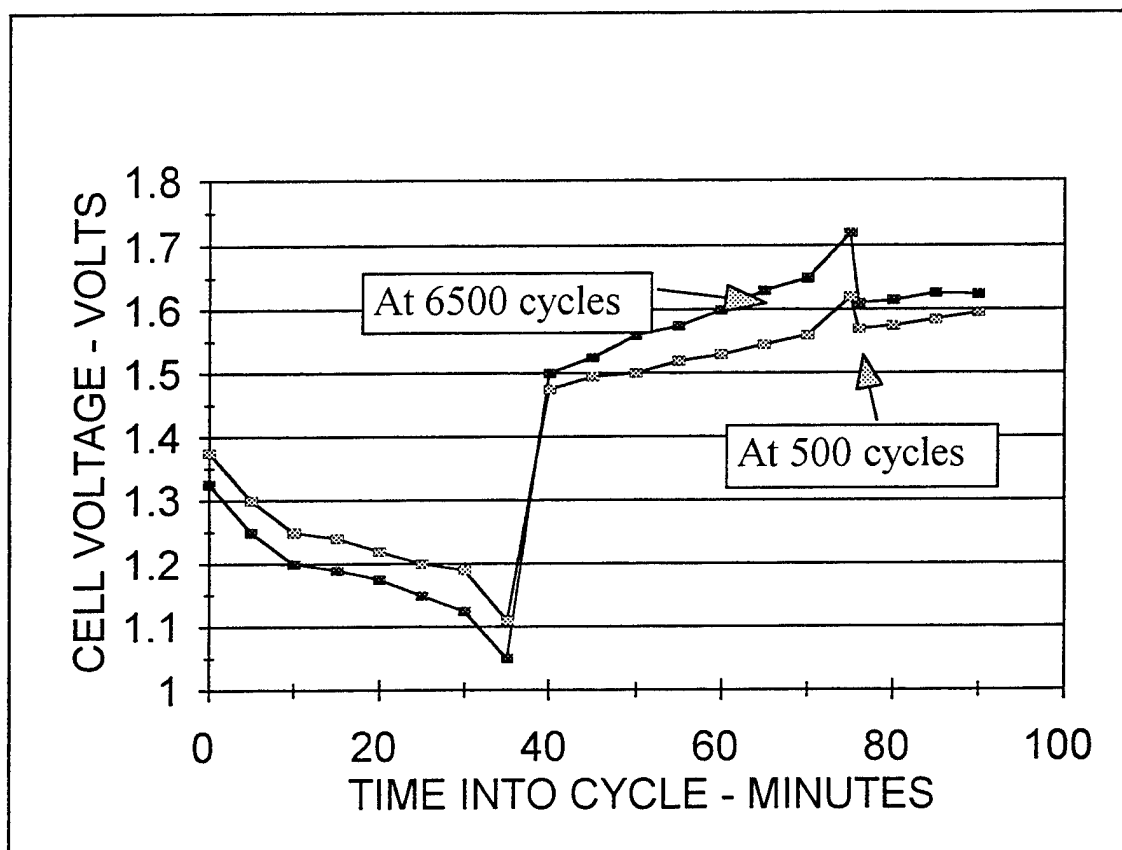
Figure 5. Charge and discharge voltage traces: 100% charge return, then trickle.

In summary, the rate of decrease of utilization of active material varies greatly, and is most likely the sum of four different mechanisms. Results from different life cycle tests and posttest analyses have suggested methods to lower this rate that are compatible with cycling cells at 60% DOD in LEO applications.

6. Cycling Recommendations

The recent status reports (Refs. 1, 2) covering the Air Force- and NASA Space Station-sponsored testing programs at the Navy facility at Crane presented some very significant findings as they relate to the cycling of cells to 60% DOD. These testing programs began in 1988. Many of the programs ended because of cell failures, others were discontinued because of lack of financial support by the sponsors, while others are still in progress. Between 400 and 500 IPV cells were tested as part of the Air Force and NASA data basing efforts.

The main findings of the testing programs at Crane are as follows:

1. Cells cycled at 60% DOD and $10°C$ always cycled longer than those cycled at $-5°C$.

2. A recharge protocol that included a taper charge as the cells approached full charge always resulted in longer cycle lives than a protocol where cells were charged at a constant current to the same charge return ratio.

3. Cells that were filled with an electrolyte of 26% potassium hydroxide always cycled longer than equivalent cells filled with 31% potassium hydroxide.

4. The cause of failure of cells cycled to 60% DOD, in all cases where failed cells were disassembled, was always attributed to degradation of the nickel electrodes.

Before NASA initiated the testing at the Navy facility at Crane, about 39 separate tests were started at NASA LeRC. Cycling was done at 35% DOD because of the mission requirement of the Space Station. A significant finding in reviewing the results of these tests is related to the recharge ratio used in the testing. Every test (except for one using 26% KOH) using a recharge ratio of 1.05 or above has failed, while every test using a recharge ratio of 1.04 or below is still running. The tests that are still running are now at about 50,000 cycles, which is equivalent to almost 9 years in LEO orbit.

One further test program is pertinent to the study of extended cycling to 60% DOD. A special cell design was developed at NASA LeRC (Ref. 8) that featured what are called catalyzed wall wicks. These are wall wicks where catalyst has been applied. The function of these wicks, as noted in Section 3, is to facilitate the recombination of the oxygen evolved during overcharge with hydrogen. The cells with these wicks are still under test and have accumulated over 50,000 cycles at 60% DOD, as of January 1998.

7. Summary

The database for nickel-hydrogen cells cycled to 60% DOD in simulated LEO applications varies widely. This report focused on conditions used during the recharge portion of the cycle and their impact on the rates of plaque corrosion and plate expansion. By selecting appropriate cell designs and teaming them with low stress level recharge protocols, long cycle life at deep DODs can be attained using current manufacturing capabilities. The gains in reduced power system weights, coupled with the documented methods of successfully cycling to 60% DOD, make a very strong case for using this cycling information in advanced high power applications envisioned for future missions. The review to date of the available cycling data would suggest several important guidelines when cycling to 60% DOD:

1. The end-of-charge voltage should be kept below 1.55 V per cell.
2. The recharge ratio should be kept below 1.05.
3. The concentration of the electrolyte should be 26%.
4. Designs featuring catalyzed wall wicks should be used.
5. Repeated recharging to the gamma phase material should be avoided.

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TECHNOLOGY OPERATIONS

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